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Integrated simulation of continuous-scale and discrete-scale radiative transfer in metal foams

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ABSTRACT

A novel integrated simulation of radiative transfer in metal foams is presented. It integrates the continuous-scale simulation with the direct discrete-scale simulation in a single computational domain. It relies on the coupling of the real discrete-scale foam geometry with the equivalent continuous-scale medium through a specially defined scale-coupled zone. This zone holds continuous but nonhomogeneous volumetric radiative properties. The scale-coupled approach is compared to the traditional continuous-scale approach using volumetric radiative properties in the equivalent participating medium and to the direct discrete-scale approach employing the real 3D foam geometry obtained by computed tomography. All the analyses are based on geometrical optics. The Monte Carlo ray-tracing procedure is used for computations of the absorbed radiative fluxes and the apparent radiative behaviors of metal foams. The results obtained by the three approaches are in tenable agreement. The scale-coupled approach is fully validated in calculating the apparent radiative behaviors of metal foams composed of very absorbing to very reflective struts and that composed of very rough to very smooth struts. This new approach leads to a reduction in computational time by approximately one order of magnitude compared to the direct discrete-scale approach. Meanwhile, it can offer information on the local geometry-dependent feature and at the same time the equivalent feature in an integrated simulation. This new approach is promising to combine the advantages of the continuous-scale approach (rapid calculations) and direct discrete-scale approach (accurate prediction of local radiative quantities).

1. Introduction

The metal foams composed of massive solid struts and accessible void spaces are typical two-phase media [1]. Analysis of radiative transfer in such complex two-phase media is of fundamental importance to many thermal applications, such as volumetric solar receivers [2], porous burners [3], thermochemical reactors [4] and heat exchangers [5]. The traditional treatment of radiative transfer in metal foam, called continuous-scale approach (CSA), uses the Radiative Transfer Equation (RTE) and volumetric average radiative properties (such as extinction coefficient, scattering albedo and scattering phase function) in equivalent continuous participating media [6]. Based on media radiation transfer theory [7], the propagation phenomena, scattering, absorption and emitting, are generally taken into account. Outside this traditional treatment, the direct discrete-scale approach (DSA) is currently attracting considerable attention. It commonly combines 3D foam geometry and Monte Carlo ray-tracing (MCRT) procedure. The foam geometry is usually derived from different shapes of idealized cells (cube [8], dodecahedron [9], tetrakaidecahedron [10] etc.) or from representations that are extracted from real foams by computed tomography technique [11,12]. To rigorously treat the radiative transfer problem, MCRT method is theoretically required [13]. General hypotheses that facilitate such radiative transfer simulations include Geometrical Optics Approximation (GOA), opaque surface for metal struts, ignoring diffraction and interference effects [14,15], etc. So far the DSA has been employed in real Al foams [16], SiC foams [17,18], NiCrAl foams [19], AlNiP foams [20], and Ni foams [21–23], etc. Precise information on geometry-dependent radiative behaviors (such as absorbed flux distribution at the strut surface) may only be accessed by means of the DSA. Compared with the continuous-scale simulations, however, such direct simulations commonly need a significantly higher computational cost [24]. So far, no methodology has become available to integrate the continuous-scale simulation with the direct discrete-scale simulation in a single computational domain.

Therefore, this contribution proposes a novel radiative transfer modeling approach which can provide integrated information of the continuous-scale simulation and the direct discrete-scale simulation. The new approach proposed is promising to be an al-

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Nomenclature

A_N	normal absorptivity
A_0	total cross-sectional area, mm^2
A_1	cross-sectional area of void phase, mm^2
A_2	cross-sectional area of solid phase, mm^2
d_p	mean pore diameter, mm
d_s	mean strut diameter, mm
E	relative error of volumetric absorbed flux
e	energy carried by each ray sampling, W
$\bar{F}$	mean amplitude of fluctuations
f_s	specularity parameter
H	height of the foam domain, mm
I	radiation intensity, W m^{-2} sr^{-1}
L	length (thickness) of the foam domain, mm
ΔL_{SCZ}	width of scale-coupled zone, mm
l_0	possible transfer distance of a ray, mm
N_S	number of rays absorbed by solid surface
N_V	number of rays absorbed by equivalent volume
n, k	complex refractive indexes of solid phase
p_0	porosity of equivalent foam
$p_{0\text{-}1}(x)$	porosity in VDZ
$p_{0\text{-}2}(x)$	porosity in SDZ
q_a	flux absorbed by foam slice, W m^{-2}
q_{in}	incident radiative flux, W m^{-2}
q_r	flux reflected by foam slice, W m^{-2}
q_S	surface absorbed flux, W m^{-2}
$\tilde{q}_S$	equivalent surface absorbed flux, W m^{-2}
q_t	flux transmitting through foam slice, W m^{-2}
$\bar{q}_V$	mean volumetric absorbed flux, W m^{-3}
$\tilde{q}_V$	equivalent volumetric absorbed flux, W m^{-3}
R_{NH}	normal-hemisphere reflectivity
$\vec{r}$	position vector, mm
ΔS_j	local surface element j
S_{V0}	specific area of equivalent foam, m^{-1}
$S_{V0\text{-}1}(x)$	specific area in VDZ, m^{-1}
$S_{V0\text{-}2}(x)$	specific area in SDZ, m^{-1}
$\vec{s}$	propagation direction vector
$\vec{s}'$	incoming direction vector
T	temperature, K
T_{NH}	normal-hemisphere transmissivity
ΔV_j	local volume element j
W	width of the foam domain, mm

Greek symbols

β_0	extinction coefficient of equivalent foam, m^{-1}
$\beta_{0\text{-}1}(x)$	extinction coefficient in VDZ, m^{-1}
$\beta_{0\text{-}1}(x)$	extinction coefficient in SDZ, m^{-1}
θ	scattering angle, °
θ_{in}	local incident angle at solid surface, °
κ_a	absorption coefficient, m^{-1}
λ	wavelength, μm
ρ_d	strut diffuse reflectivity
$\rho_{N,d}$	strut normal diffuse reflectivity
$\rho_{N,s}$	strut normal specular reflectivity
ρ_s	strut specular reflectivity
σ_s	scattering coefficient, m^{-1}
σ_{RMS}	root mean square of rough surface, μm
ζ	random number
Φ_0	scattering phase function
Ω	solid angle, sr
ω_0	scattering albedo

Subscripts

a	absorbed
d	diffuse
in	incident
N	normal
NH	normal-hemispherical
r	reflected
S	surface
s	specular
t	transmitted
V	volume
λ	spectral
0	equivalent foam
1	void phase
2	solid phase

Acronyms

CSA	continuous-scale approach
CSZ	continuous-scale zone
DSA	discrete-scale approach
DSZ	discrete-scale zone
GOA	Geometrical Optics Approximation
MCRT	Monte Carlo ray-tracing
RTE	Radiative Transfer Equation
SCA	scale-coupled approach
SCZ	scale-coupled zone
SDZ	solid-dominated zone
VDZ	void-dominated zone

ternative to the direct DSA which considers the exact distribution of solid and fluid phase in the medium and the classical CSA which assimilates the porous material to a continuous semi-transparent medium with homogeneous radiative properties. This new approach can be able to combine the advantages of the CSA (rapid calculations) and DSA (accurate prediction of local radiative quantities). To achieve these goals, the paper is organized as follows. In Section 2.1, the basic models of radiative transfer in metal foams are described. The details of the principles and concepts of the DSA and CSA are subsequently introduced in Sections 2.2 and 2.3, respectively. In Section 2.4, a new scale-coupled approach (SCA) is proposed to integrate the real discrete-scale foam geometry with the equivalent continuous-scale medium. After comparisons with the existing experimental results (Section 3.1), the capability and reliability of the SCA proposed in calculating the local absorbed radiative fluxes (Section 3.2) and the apparent radiative behaviors (Section 3.3) of metal foams is fully validated. This new approach is also promising in foam-based high-temperature applications. For example in solar porous receivers, most of concentrated solar radiation commonly attenuates within a small region near to the inlet surface [25]. Thus embedding small pieces of real foam geometry into the inlet region of the continuous semi-transparent medium will improve the computational accuracy of radiative transfer caused by concentrated solar radiation. This treatment can facilitate the achievement of precise radiative transfer at key locations and at the same time cope with the challenge of computational resources.

2. Model and method

2.1. Model description

Fig. 1 illustrates the computational domain for the radiative transfer in metal foams. The computational domain is set to a cuboid with an inlet face and an outlet face. It is assumed that the domain is symmetrically continued in the lateral directions, thus